

Modelling water temperatures at depths
within the stream substrate at Catamaran
Brook (NB): potential implication of climate
change

D. Caissie and M.G. Satish

Fisheries and Oceans
Gulf Fisheries Centre, Science Branch
Diadromous Fish Division
P.O. Box 5030, Moncton, NB, E1C 9B6

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**Modelling water temperatures at depths within the stream substrate
of Catamaran Brook (NB): potential implication of climate change¹**

by

Daniel Caissie

and

Mysore G. Satish²

**Department of Fisheries and Oceans
Gulf Fisheries Centre, Science Branch
Diadromous Fish Division
P.O. Box 5030, Moncton, NB, E1C 9B6**

¹ Contribution No. 62 of the Catamaran Brook Habitat Research Project

² Dalhousie University, Department of Civil Engineering, Halifax, Nova Scotia, B3J 2X4

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ABSTRACT

Caissie, D. and M.G. Satish. 2001. Modelling water temperatures at depths within the stream substrate of Catamaran Brook (NB): potential implication of climate change. *Can. Tech. Rep. Fish. Aquat. Sci.* 2365: 27p.

Intragravel water temperatures are highly linked to both surface water and groundwater temperatures conditions. Water temperatures within the stream substrate are important, not only for aquatic insects but also for the incubation of salmonid eggs. In the present study, a water temperature diffusion model (finite difference) was calibrated using existing intragravel temperature data at a depth of 0.2 m. This depth was of particular interest in relation to the depth salmonid eggs. Once calibrated, the model was used to predict intragravel temperatures at different depths within the stream substrate. A sensitivity analysis was carried out to determine the effect of a vertical velocity component on intragravel temperatures. A sensitivity analysis was also carried out to determine the effect of an increase in groundwater temperature due to global warming.

Results showed that the diffusion type model effectively modeled intragravel temperatures. Good agreement was observed between predicted and observed intragravel temperatures at depth of 0.2 m, with a root-mean-square error of 0.35°C (during the study period of July 11 to September 11, 1996). Mean differences between predicted and observed temperatures were less than 0.2 °C. Results showed that stream discharge can influence intragravel temperatures, especially when discharge was above the mean annual discharge. The vertical velocity component can influence intragravel temperatures at higher flows (e.g. 0.01 m/hr). At such vertical flow conditions, the difference in intragravel temperatures could be expected in the order of 1.5-1.8 °C at a depth of 0.2 m depending on the direction of flow. For lower vertical flow components, such as 0.001 m/hr, the difference in intragravel temperatures becomes much less, in the range of 0.1-0.2 °C. Finally, results showed that an increase in groundwater temperatures by +1.5 to +3.0 °C, could result in an increase of +0.3 to +0.6 °C at a depth of 0.2 m.

RÉSUMÉ

Caissie, D. and M.G. Satish. 2001. Modelling water temperatures at depths within the stream substrate of Catamaran Brook (NB): potential implication of climate change. Can. Tech. Rep. Fish. Aquat. Sci. 2365: 27p.

La température de l'eau à dans substrat est grandement liée à la température de l'eau souterraine et celle de l'eau de surface. Cette température de l'eau au niveau du substrat est importante, non seulement pour les insectes aquatiques mais aussi pour l'incubation des œufs des salmonidés. Dans la présente étude, un modèle de diffusion de température de l'eau à l'intérieur du substrat (par différence finie) a été calibré en utilisant des données de température de l'eau à une profondeur de 0.2 m. Cette profondeur possède un intérêt particulier pour l'incubation des œufs des salmonidés. Après le calage du modèle, celui-ci a été utilisé pour prédire la température de l'eau à différentes profondeurs à l'intérieur sur substrat. Une analyse de sensibilité a été effectuée afin d'étudier l'effet d'une augmentation de la température de l'eau souterraine sur la température du substrat suite à un réchauffement climatique.

Les résultats ont démontré que le modèle de diffusion peut effectivement prédire la température de l'eau à l'intérieur du substrat. Une bonne correspondance a été observée entre la température prédite et observée à une profondeur de 0.2 m avec une erreur quadratique moyenne de 0.35°C (durant la période en étude, 11 juillet au 11 septembre). La différence moyenne entre la température de l'eau prédite et observée était de moins de 0.2 °C. Les résultats ont également démontré que le débit de la rivière peut avoir une influence sur la température de l'eau dans le substrat, surtout lorsque le débit est supérieur au débit moyen. Un écoulement vertical de l'eau à l'intérieur du substrat peut aussi avoir une influence sur la température de l'eau dans le substrat lorsque l'écoulement est important (par exemple, 0.01 m/heure). Pour un tel écoulement vertical, une différence dans la température de l'eau à l'intérieur du substrat à 0.2 m de profondeur peut atteindre 1.5-1.8 °C en fonction de la direction de l'écoulement. Pour un écoulement vertical inférieur, i.e. 0.001 m/heure, la différence de température est plus faible, d'environ 0.1-0.2 °C. Finalement, les résultats de cette étude démontrent qu'une augmentation de +1.5 à + 3.0 °C de la température de l'eau souterraine, peut produire une augmentation de +0.3 à +0.6°C dans la température de l'eau du substrat à 0.2m de profondeur.

1.0 INTRODUCTION

Stream water and intragravel (i.e. within the substrate) water temperatures are important parameters in ecological studies of rivers. Intragravel temperatures can influence chemical conditions as well as biological processes in streams. For instance, intragravel water temperature is related to the timing of hatching of salmonid eggs (Johnston 1997). The relationship between aquatic insect development and temperature is also well documented in the literature (Cazaubon and Giudicelli 1999). Surface water temperatures are often monitored in streams, however few studies have monitored or modelled water temperature patterns within the stream bed. Although surface water temperatures influence intragravel temperatures, surface water temperatures alone do not accurately reflect the thermal environment experienced by biota within the substrate.

Within the stream substrate zone, also called hyporheic zone, an interchange of surface water and groundwater occurs. Devices used to study the interaction between stream water and hyporheic water conditions include seepage meters, mini-peizometers and dye injection techniques (Boulton 1993). Within the substrate, the temperature is diffused such that surface water temperatures are observed at the bed level (i.e. stream bottom) and groundwater temperatures are observed at a specific depth within the stream bed.

Large differences have been observed between surface and intragravel temperature conditions, depending on season and location (Hartman and Leahy 1983, Shepherd et al. 1986). For example, Hartman and Leahy (1983) found that intragravel temperatures (30 cm depth) in Carnation Creek (B.C.) could reach 5.7 °C higher than surface waters in winter and 3.7 °C cooler in summer. Both surface water and groundwater temperatures are important to determine changes in temperatures within the stream substrate. Also, any changes in both surface water and groundwater temperatures will ultimately result in changes to intragravel temperatures. For instance, as a result of climate change, it is expected that both surface and groundwater temperatures will increase (Meisner et al. 1988). In Eastern Canada, air temperature is projected to increase by 2 to 6 °C over the next 100 years (Parks Canada 1999). Since river water (i.e.

surface water) and groundwater temperatures are linked to air temperatures, they are also expected to increase during this period.

Although many studies have looked at the physical and chemical conditions of intragravel waters in streams, little is known about modelling intragravel water temperatures in relation to surface water temperatures and groundwater conditions. Therefore, the objective of the present study was to model intragravel water temperatures in Catamaran Brook, (NB) during the summer period in 1996. The specific objectives were: a) to calibrate a finite difference diffusion model using existing intragravel temperature data, b) to model intragravel temperatures at different depth within the stream substrate, and c) to carry out a sensitivity analysis based on the vertical velocity component and increases in groundwater temperatures.

2.0 MATERIALS AND METHODS

2.1 Study area

This study was conducted in Catamaran Brook (46° 52.7' N, 66° 06.0' W), a small drainage basin (51 km²) in the Miramichi River system of New Brunswick (Fig. 1). The present forest cover is mainly second-growth forest, consisting of mostly mature species estimated as 65% coniferous and 35% deciduous (Cunjak et al. 1990; St. Hilaire et al. 1996). Atlantic salmon (*Salmo salar*) is the most common fish species in Catamaran Brook, and anadromous adults enter the brook annually to spawn in late October and early November. Brook trout (*Salvelinus fontinalis*) are common in the headwater portions of the basin and in Catamaran Lake (Cunjak et al. 1993).

Meteorological data (air temperature, precipitation) have been collected at a weather station located at mid-basin (Fig. 1) since 1990. Annual precipitation in the area ranges from 860 - 1365 mm, with an average of 1142 mm (Caissie and El-Jabi 1995). January has the coldest mean monthly air temperature, with a mean of -11.8 °C. July is the warmest month, with a mean monthly air temperature of 18.8 °C. The mean annual air temperature in Catamaran Brook was calculated at 4.4 °C, using long-term meteorological data in the area.

Stream discharge has been monitored at a hydrometric gauging station located at mid-basin (Fig. 1) since October 1989. The mean annual flow for Catamaran Brook has been calculated at $0.69 \text{ m}^3/\text{s}$ or 754 mm of runoff. The highest measured discharge in the period of record was recorded during the spring flood period of late April to early May, 1991, with a peak value of $13 \text{ m}^3/\text{s}$ on May 3, 1991. The lowest recorded discharge was $0.016 \text{ m}^3/\text{s}$, recorded September 3, 1994.

2.2 Monitoring of surface and intragravel water temperatures

Surface water temperatures have been recorded at many sites within the Catamaran Brook basin. The site of interest in the present study was located approximately 20 m below the hydrometric station at mid-basin (Fig. 1). The stream water temperature sensor was installed at approximately 1 m from the bank near the stream bottom, and recorded surface water temperatures on an hourly basis. The sensor (Model 107B, from Campbell Scientific Canada Corp., 1992) incorporates a Fenwal Electronic thermister probe, and typically has an error of less than 0.2°C for the range of -30 to $+40^\circ\text{C}$. The sensor accuracy was verified against a mercury thermometer (0.1°C), and recorded values within 0.1°C of actual stream water temperatures. Localised variations in stream water temperatures were monitored by taking measurements with the mercury thermometer at 0.5 m intervals from bank to bank. No variations were observed due to the well mixed nature of the brook water.

The intragravel water temperature sensor was the same type as that used for surface waters. The sensor was installed at a depth of 20 cm into the substrate, approximately mid-stream (Fig. 1), where Atlantic salmon have been observed spawning in the past. Intragravel water temperatures during the mid-summer of 1996 were used in the present study for modelling purposes, a period where diurnal temperatures fluctuations were relatively high in both surface and intragravel waters. The study period was from July 11, 1996 (day 192) to September 11, 1996 (day 254), which included the warm summer period. Both sensors were hooked to a CR10 Data Logger (Campbell Scientific Canada Corp. 1992), and water temperatures were monitored

every second during the last minute of the hour (i.e. from minute 59 to 60) to establish a mean value corresponding to the hourly reading.

2.3 Intragravel temperature diffusion model

The heat exchange between the surface water and intragravel temperatures has been described in the literature by Stallman (1965). When a vertical flow component is present the one-dimensional diffusion equation takes the following form:

$$[1] \quad k \frac{\partial^2 T}{\partial z^2} - v_z c_w \rho_w \frac{\partial T}{\partial z} = c \rho \frac{\partial T}{\partial t}$$

where k = thermal conduction of the rock-fluid matrix ($\text{kcal/hr m}^3 \text{ } ^\circ\text{C}$);

T = temperature in $^\circ\text{C}$ at depth with time (hr);

c_w = heat capacity of the fluid ($\text{kcal/m}^3 \text{ } ^\circ\text{C}$);

ρ_w = density of the fluid (e.g. water = 1000 kg/m^3);

c = heat capacity of the rock-fluid matrix ($\text{kcal/m}^3 \text{ } ^\circ\text{C}$);

ρ = density of the rock-fluid matrix (kg/m^3);

v_z = vertical velocity component, negative for upwelling water (m/hr);

z = depth within the substrate (m);

each term in equation [1] can be expressed with the following explicit finite difference approximation:

$$[2] \quad \frac{\partial T}{\partial t} \cong \frac{T_z^{i+1} - T_z^i}{\Delta t}$$

$$[3] \quad \frac{\partial T}{\partial z} \cong \frac{T_{z+1}^i - T_{z-1}^i}{2\Delta z}$$

and

$$[4] \quad \frac{\partial^2 T}{\partial z^2} \equiv \frac{T'_{z+1} - 2T'_z + T'_{z-1}}{\Delta z^2}$$

When equation [2], [3] and [4] are substituted in equation [1], a finite difference model was obtained, which is represented by the following equation:

$$[5] \quad k \left[\frac{T'_{z+1} - 2T'_z + T'_{z-1}}{\Delta z^2} \right] - v_z c_w \rho_w \left[\frac{T'_{z+1} - T'_{z-1}}{2\Delta z} \right] = \rho c \left[\frac{T'^{t+1}_i - T'_i}{\Delta t} \right]$$

after rearranging the above equation by assembling the temperature terms (T) together, the following equation can be obtained to express the temperature (T) with depth (z) at time step $t+1$:

$$[6] \quad T'^{t+1}_z = \frac{k\Delta t}{\rho c \Delta z^2} \left(1 + \frac{\rho_w c_w v_z \Delta z}{2k} \right) T'_{z-1} + \frac{k\Delta t}{\rho c \Delta z^2} \left(1 - \frac{\rho_w c_w v_z \Delta z}{2k} \right) T'_{z+1} + \left(1 - \frac{2k\Delta t}{\rho c \Delta z^2} \right) T'_z$$

where all parameters were defined previously. Past studies (Stallman 1965) have shown that such explicit scheme is numerically stable when the coefficient in front of the first term on the right hand side of equation [6] is less than 0.5, i.e.:

$$[7] \quad r = \frac{k \Delta t}{\rho c \Delta z^2}$$

Therefore to assure stability of equation [6], the value of r (equation [7]) should be less than 0.5.

A computer program was written in BASIC to solve equation [6] (see appendix) for different physical conditions and groundwater temperatures. Intragravel temperatures were simulated for different depths within the stream substrate. Simulated data were compared to actual measurement of intragravel water temperatures at a depth of 0.2 m. In the present study,

the intragravel temperature model was calibrated with a no vertical flow condition (i.e. $v_z = 0$). Following the modelling, a sensitivity analysis was carried out to observe the influence of a vertical flow component on the intragravel temperatures and also the influence of the groundwater temperatures. Results of the sensitivity analysis were carried out at a depth of 0.2 m, which is of particular interest for the incubation of Atlantic salmon eggs as this is approximately the depth at which they bury their eggs.

3.0 RESULTS

In order to run the model, the following parameters needed to be estimated: a) c_w = heat capacity of the fluid; b) ρ_w = density of the fluid; c) c = heat capacity of the rock-fluid matrix and d) ρ = density of the rock-fluid matrix. The density of the fluid, which in this study is water, was assumed constant at 1000 kg/m^3 . The heat capacity of the fluid (i.e. water) was used at $1000 \text{ kcal/m}^3 \text{ }^\circ\text{C}$. The density of the rock-fluid matrix was assumed at 1700 kg/m^3 while the heat capacity of the rock-fluid matrix was assumed at $600 \text{ kcal/m}^3 \text{ }^\circ\text{C}$ based on data and graphs from Lapham (1989). The groundwater temperature at Catamaran Brook was monitored at the meteorological station at $6.5 \text{ }^\circ\text{C}$ (mean value) and is relatively constant throughout the year. Therefore, a constant groundwater temperature of $6.5 \text{ }^\circ\text{C}$ was assumed at a depth of 1 m into the substrate.

Using the above parameters, the model was successfully calibrated using a thermal conduction of the rock-fluid matrix (k) of $4000 \text{ kcal/ hr m}^3 \text{ }^\circ\text{C}$, which is within the values reported in Lapham (1989). Results of the modelled and measured intragravel temperatures at a depth of 0.2 m are presented in Figure 2 as well as modelled values at depths of 0.4 m and 0.6 m.

It can be observed that the diurnal variations in surface water temperatures are much more important than those within the substrate (Figure 2). Also, temperatures within substrate become more stable as depth increases (e.g. 0.4 m vs 0.6 m). The mean surface water temperature during the study period was calculated at $14.7 \text{ }^\circ\text{C}$ while the intragravel temperatures were calculated at $12.9 \text{ }^\circ\text{C}$, $11.0 \text{ }^\circ\text{C}$ and $9.2 \text{ }^\circ\text{C}$ for depths of 0.2 m, 0.4 m, and 0.6 m respectively. The root-mean-

square error (rmse) is often used to compare the model's performance (Caissie et al. 1998). The rmse calculation was carried out using the measured and modelled intragravel water temperature data at a depth of 0.2 m. The calculated root-mean-square error during the period under investigation was 0.35 °C.

Simulated intragravel temperatures were closer to observed values after day 212 (July 31; Figure 2). The model underestimated intragravel temperatures before July 31. Stream discharge data indicated that streamflow can have an impact on the modelling. For instance, the river discharge was relatively high in July (Figure 3) due to high precipitation events. Following day 212 (July 31), discharges were below 0.5 m³/s or below the mean annual average conditions and results suggest that the modelling was better under such flow conditions.

The influence of the vertical velocity component on intragravel temperatures was also studied at Catamaran Brook for a depth of 0.2 m, depth corresponding to that of incubation of Atlantic salmon eggs. Estimation of seepage flux in rivers using seepage meters indicated that the vertical velocity component is typically less than 0.01 m/hr (0.24 m/day) and very often close to 0.001 m/hr (0.024 m/day) (Cruickshanks et al. 1988). Results of the modelling indicated that for vertical velocity of +0.001 to -0.001 m/hr, only small changes in intragravel water temperature were observed (Figure 4). For instance, the mean overall (day 192 to day 254) intragravel water temperature at 0.2 m was simulated at 12.9 °C with a no vertical flow component (Table 1). The mean intragravel temperature was calculated at 12.7 °C for upwelling water (-0.001 m/hr) and 13.0 °C for downwelling water (+0.001 m/hr), a difference of less than 0.2 °C. In the case where the vertical flow component is high, more important differences can be observed in intragravel temperatures. For upwelling water of -0.01 m/hr the mean temperature was calculated at 11.1 °C, i.e. 1.8 °C colder than the no vertical flow conditions. For downwelling water, the intragravel temperature was close to surface water conditions. During the studied period the mean intragravel temperature with a vertical velocity component of +0.01 m/hr was calculated at 14.0 °C or 1.1°C warmer than the no vertical flow condition. This

temperature of 14.0 °C was comparable to the average surface water temperature of 14.7 °C (Table 1).

A sensitivity of the model to the groundwater temperatures was carried out. For instance, the measured groundwater temperatures at Catamaran Brook are at 6.5 °C. If groundwater temperatures would be increased by +1.5°C to +3.0 °C, how would the intragravel temperature increased at a depth of 0.2 m. Results of the modelling are presented in Figure 5, for groundwater temperatures of 6.5 °C, 8.0 °C (+1.5 °C) and 9.5 °C (+3.0 °C). It was observed that the intragravel temperatures at the depth of incubating eggs would increase slightly for both conditions. The mean intragravel water temperature was calculated at 13.2 °C for a groundwater temperature of 8.0 °C (Table 1), therefore an increase of 0.3 °C compared to present conditions. For a groundwater temperature of 9.0 °C, in mean intragravel temperature was calculated at 13.5 °C, which represents an increase of 0.6 °C compared to present groundwater temperatures.

4.0 DISCUSSION AND CONCLUSIONS

The present study discussed the importance of modelling intragravel temperatures to better understand the thermal regime within the stream substrate. This should help understand implication of intragravel temperatures on aquatic resources in general and on the incubation of salmonid eggs under natural conditions or as a result of potential climate change.

Results showed that it was possible to model intragravel temperatures within the stream substrate with a one-dimensional diffusion model. Good agreement was observed between measured and predicted intragravel water temperatures with a root-mean-square error of only 0.35 °C. The mean difference in observed vs predicted intragravel temperature was also very low at only 0.2 °C. The modelling showed, as expected, that water temperature in the substrate becomes more stable with depth and with smaller diurnal variations.

The present study showed the importance of the vertical flow component on the intragravel water temperatures. With a modelling that considered a vertical flow in the range of

those observed in the literature, it was demonstrated that the intragravel water temperatures can be different depending on the magnitude of the vertical flow conditions. A difference in temperatures, on average, of as much as 1.8 °C at a depth of 0.2 m can be observed when the vertical flow component is high. It was also noted that upwelling water tends to cool intragravel water temperatures while downwelling water tends to warm the intragravel conditions during summer conditions. It should be noted that the reverse would be expected during winter where surface water temperatures are generally colder than the groundwater temperatures.

The present study also looked at the increase of intragravel water temperatures due to an increase of groundwater temperature, which is expected under global warming (Meisner et al. 1988). Good relations existed between mean annual air temperature and groundwater temperatures, except for high latitudes. Shallow groundwater temperatures are usually 1.1-1.7°C warmer than the mean annual air temperature (Meisner et al. 1988). The increase in mean air temperature in the Catamaran Brook area is projected in the range of 2 to 6 °C and this could result in a significant increase in groundwater temperatures. In this study, we chose to model an increase of +1.5 °C and 3.0 °C, although the increase in groundwater temperature could exceed these values.

The modelling showed that an increase in groundwater temperature of +1.5°C resulted in increased intragravel water temperatures of 0.3 °C at a depth of 0.2 m. If the increase in groundwater temperature was in the order of +3.0 °C, then the expected increase in intragravel temperatures would be in the order of 0.6°C. Increase in groundwater temperatures due to global warming would also be accompanied with an increase in surface water temperatures, which was not taken into consideration in the present study. It would therefore be expected that the overall increase in intragravel water temperatures would be higher than 0.3 °C to 0.6 °C. Such an increase in groundwater temperatures would ultimately affect the development of aquatic insects and the timing of fry emergence. The development of Atlantic salmon eggs requires approximately 800 accumulated thermal units (ATU, degree-days) from fertilisation to first feeding (US Fish and Wildlife Service, 1988). Egg incubation in Catamaran Brook is usually

from mid-November to mid-June, or during approximately 210 days. With an increase of almost 0.5 °C or more at a depth of 0.2 m in the stream substrate, the timing of fry emergence could be earlier by as much as 25 days.

In conclusion, this study showed that any changes to either surface water or groundwater temperatures will ultimately result in changes to intragravel water temperatures conditions, at the depth of egg incubation. Furthermore, the vertical flow component can be important in determining the thermal regime of intragravel temperatures, especially when the vertical velocity is high. Any changes in the vertical flow component due to land use activities such as timber harvesting or other could potentially change the temperature regime within the stream substrate. For instance, it has been demonstrated that deforestation tends to increase the groundwater levels within cut blocks (Hetherington 1982). When these cut blocks are adjacent to streams, the increase in gradient (i.e. pressure head) could result in higher vertical flow component in the stream. This could result in potential changes to the intragravel thermal regime.

Finally, groundwater temperature in a most region is closely linked to air temperature and any increases due to global warming will result in increases in groundwater temperature. Such increases in groundwater temperatures will also be reflected in the intragravel water temperature regime. With projected increases of 2 to 6 °C in air temperatures in the Catamaran Brook area over the next 100 years, the timing of salmon fry emergence could be earlier by as much as 25 days based on modelling results and literature data on the development of salmon eggs.

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Table 1. Mean intragravel water temperatures (°C) during the study period (day 192 to 254) at Catamaran Brook for varied vertical flow conditions and for increased groundwater temperatures of +1.5 °C and +3.0 °C.

Parameter	Model	Measured
Surface water temperature		14.7
Depth of 0.2 m ($v_z = 0.0$ m/hr)	12.9	13.1
Depth of 0.4 m ($v_z = 0.0$ m/hr)	11.0	
Depth of 0.6 m ($v_z = 0.0$ m/hr)	9.2	
Depth of 0.2 m ($v_z = -0.001$ m/hr)	12.7	
Depth of 0.2 m ($v_z = +0.001$ m/hr)	13.0	
Depth of 0.2 m ($v_z = -0.01$ m/hr)	11.1	
Depth of 0.2 m ($v_z = +0.01$ m/hr)	14.0	
Depth of 0.2 m (groundwater +1.5°C)	13.2	
Depth of 0.2 m (groundwater +3.0°C)	13.5	

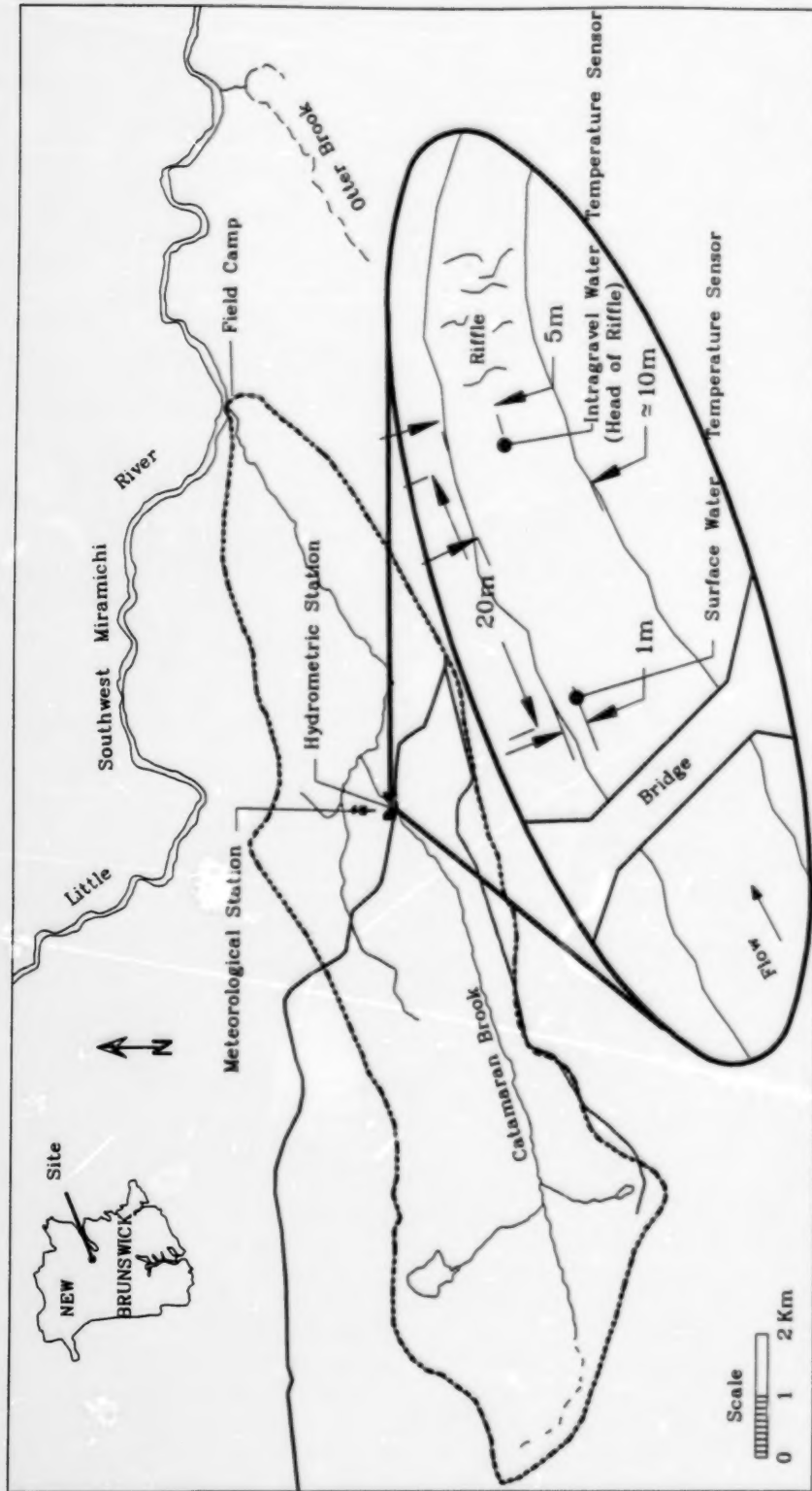


Figure 1. Map of Catamaran Brook showing the location of the hydrometric station, meteorological station and water temperature monitoring sites.

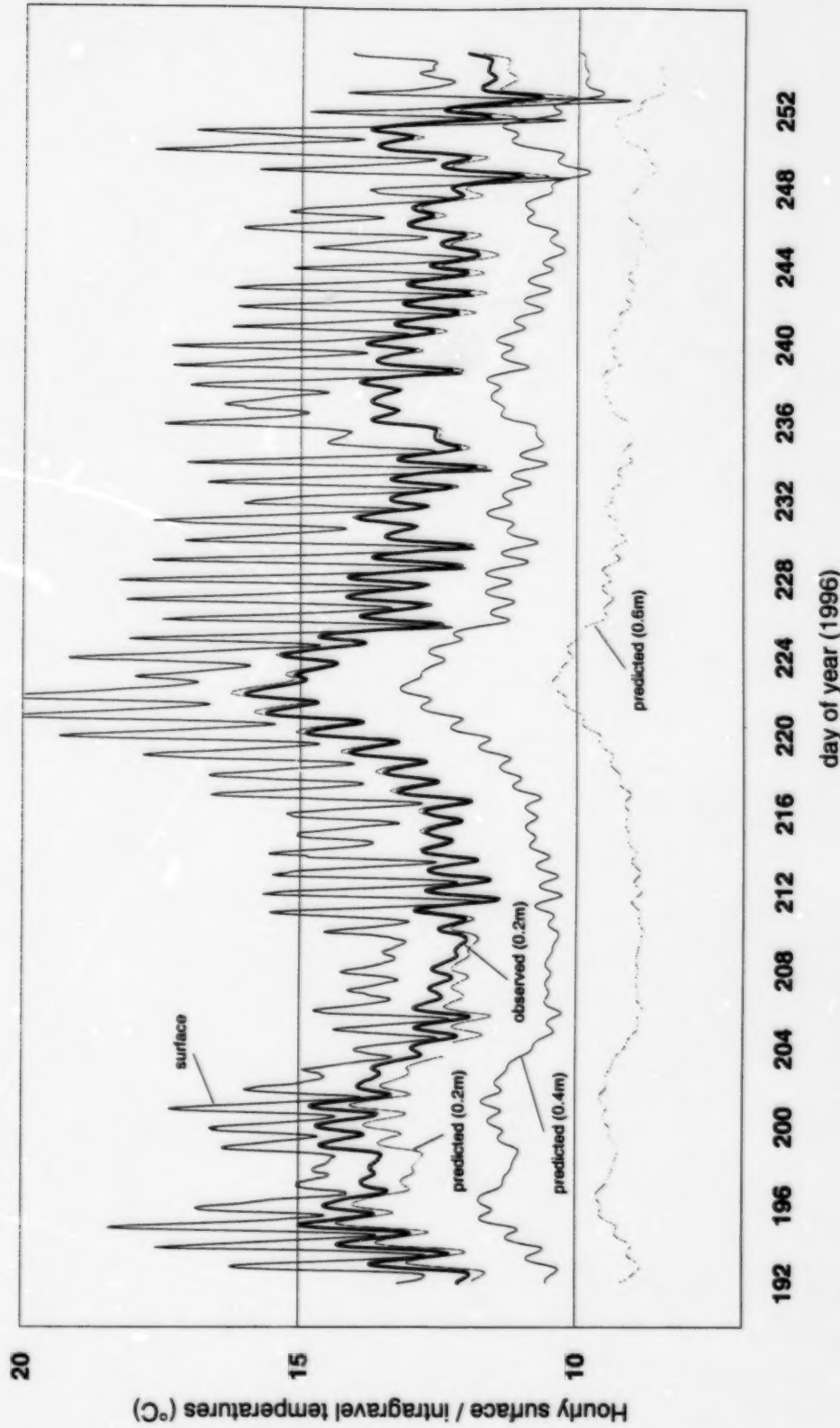


Figure 2. Simulated intragravel water temperatures at Catamaran Brook for different depths within the substrate and comparison of simulated data to observed data at a depth of 0.2 m

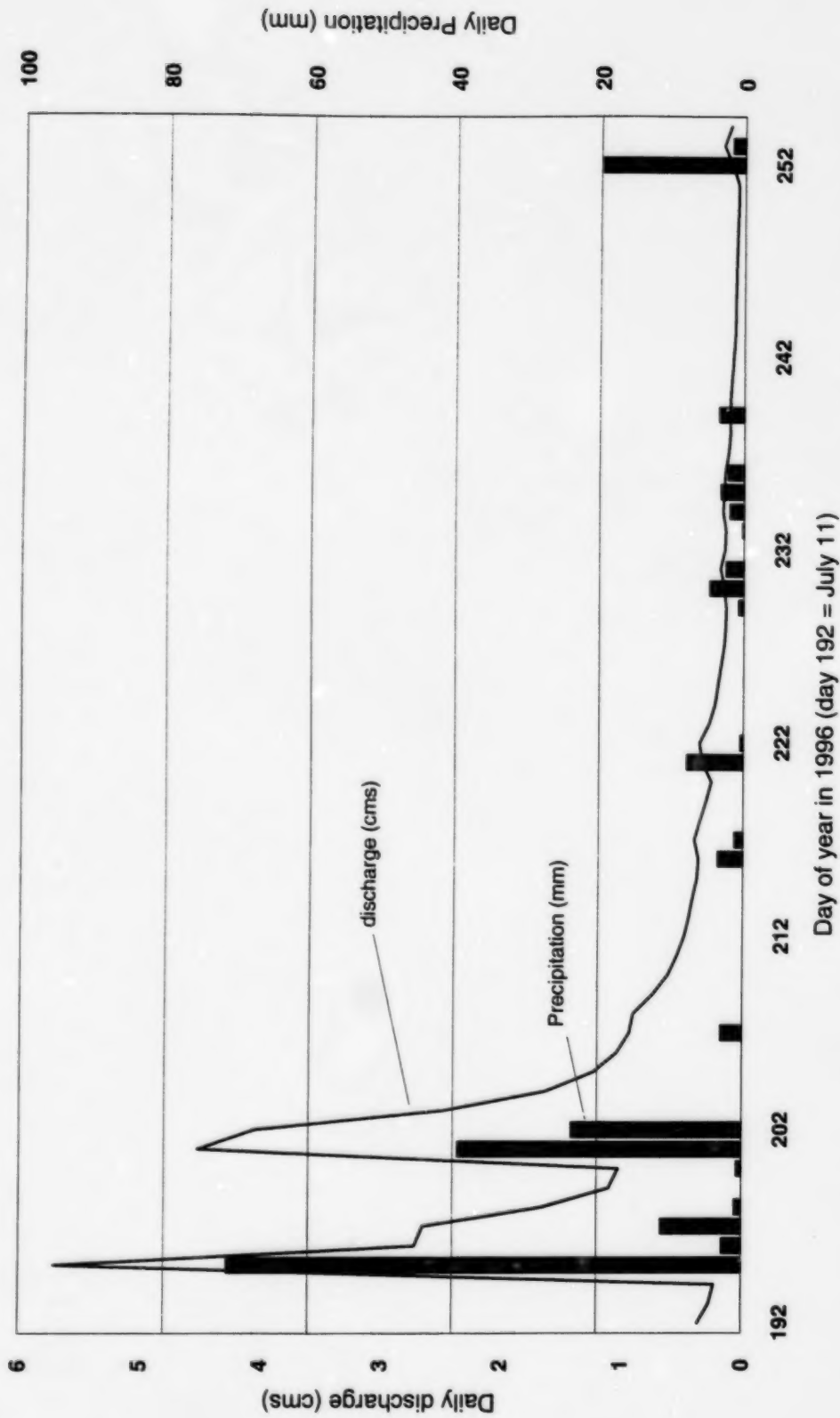


Figure 3. Catamaran Brook daily discharge (cms) and precipitation (mm) from July 11 (day 192) to Sept. 11, 1996 (day 254)

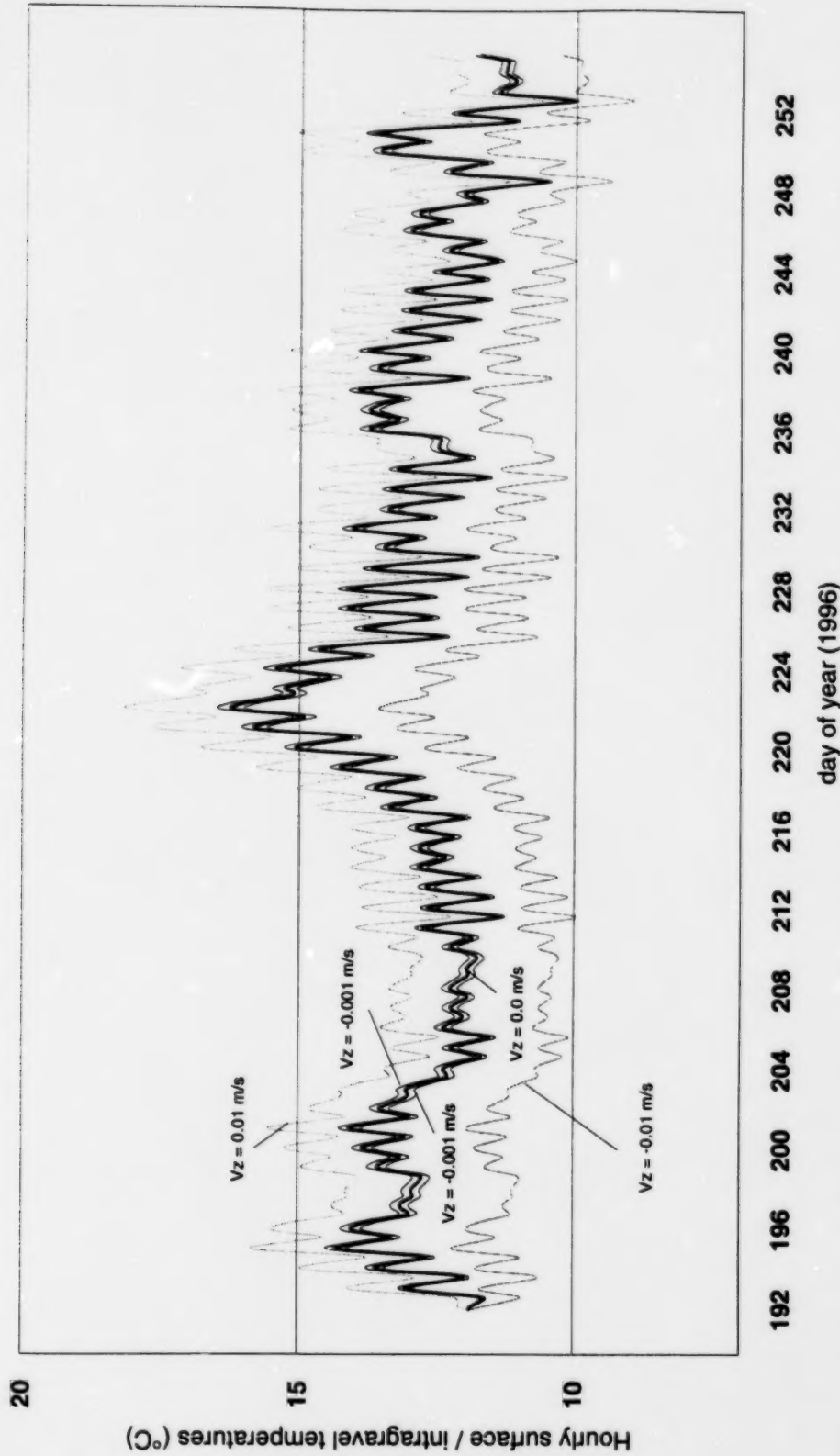


Figure 4. Simulated intragravel water temperatures at Catamaran Brook at a depth of 0.2 m under different vertical velocity components (V_z). (Bold line = predicted at 0.2 m for $V_z = 0.0 \text{ m/s}$)

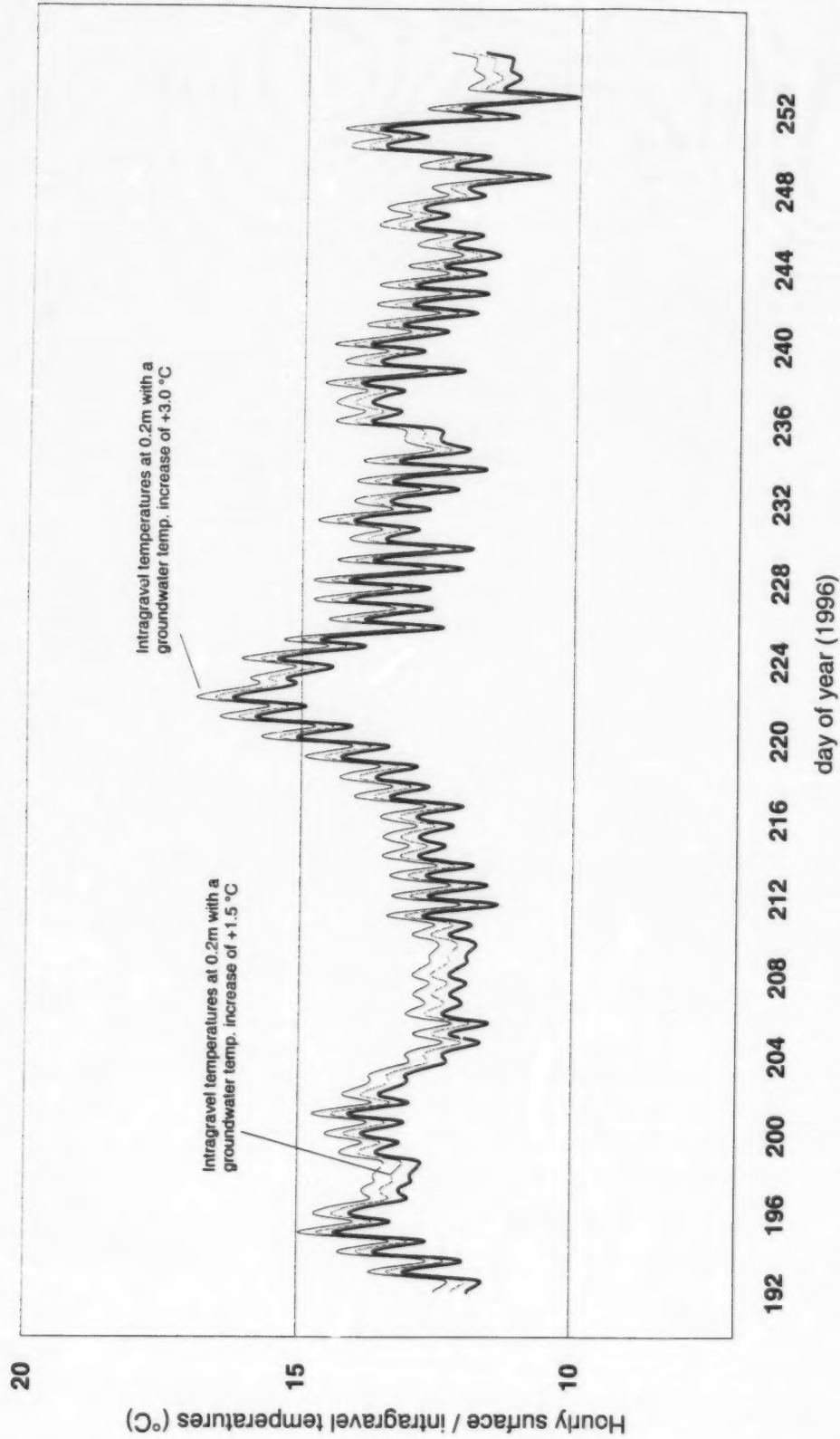


Figure 5. Simulated intragravel water temperatures at Catamaran Brook at a depth of 0.2 m under varied increases in groundwater temperatures, +1.5 °C and +3.0 °C. (Bold line = predicted at 0.2m).

Appendix A

Computer Program in BASIC

INTRA.BAS

```
=====
```

NUMERICAL HEAT TRANSFER

Modelling of water temperature profile within the substrate
with and without a vertical velocity component.

Fisheries and Oceans Canada
Diadromous Fish Division
P.O. Box 5030
Moncton, NB
Canada, E1C 9B6

```
=====
```

```
=====
```

\$DYNAMIC

```
  DIM INTRA(1600), SURF(1600), T(20, 1600)
  DIM INTRA(160), SURF(160), T(20, 160)
```

1. Reading input data and parameters.

```
CLS : PRINT : PRINT
INPUT " Enter fluid-rock density (e.g. 1.7)"; RHO
INPUT " Enter heat capacity of fluid-rock matrix (e.g. 0.6)"; HC
INPUT " Enter fluid density (e.g. water = 1.0)"; RHO
INPUT " Enter heat capacity of fluid (e.g. water = 1.0)"; HCW
INPUT " Enter delta T(hour)"; DT
INPUT " Enter delta Z(meter)"; DZ
INPUT " Enter vertical velocity (m/hour)"; VZ
INPUT " Enter thermal conductivity (k)"; THERMK
INPUT " Enter groundwater temperature °C (e.g. 6.5 °C)"; GRDWT
INPUT " Enter number of grid points in the z direction (max =
20)"; GRIDZ
R = (THERMK * DT) / (RHO * HC * DZ * DZ)
R1 = THERMK / (RHO * HC)
PRINT USING " Value of R (<0.5 for stability) #.### "; R
PRINT USING " Bulk diffusion = #.####"; R1
PRINT
INPUT " Enter data file name "; FILE1$
INPUT " Enter output file name "; FILE2$
OPEN "I", #1, FILE1$
OPEN "O", #2, FILE2$

I = 0
DO WHILE NOT EOF(1)
  I = I + 1
  INPUT #1, AN, JD, HOUR, INTRA(I), SURF(I)
  PRINT I, AN, JD, HOUR, INTRA(I), SURF(I)
LOOP
```

2. TT = Total time.

```
TT = I
PRINT "Total number of hours = "; TT

INPUT " Press C to continue"; CH1$
```

3. Set-up initial temperature profil (linear with depth).

```

FOR Z = 1 TO GRIDZ
  T(Z, 1) = SURF(1) + ((GRDWT - SURF(1)) * (Z - 1) / GRIDZ)
  T(Z, TT) = SURF(TT) + ((GRDWT - SURF(TT)) * (Z - 1) / GRIDZ)
NEXT Z

4. Set-up surface/bottom boundry conditions.
   Surface = stream water temperatures.
   Bottom = groundwater temperatures.

   FOR TI = 1 TO TT
     T(1, TI) = SURF(TI)
     T(GRIDZ, TI) = GRDWT
   NEXT TI

5. Set-up interior initial conditions to zero degree C.

   FOR Z = 2 TO GRIDZ - 1
     FOR TI = 2 TO TT
       T(Z, TI) = 0
     NEXT TI
   NEXT Z

   NUMIT = 0

6. Iterations using explicit method.

   FOR K = 1 TO 100
     AMAX = 0
     NUMIT = NUMIT + 1
     FOR TI = 2 TO TT - 1
       FOR Z = 2 TO GRIDZ - 1
         OLDVAL = T(Z, TI)
         A1 = R * T(Z - 1, TI - 1) * (1 + ((RHOW * HCW * VZ * DZ) / (2 *
THERMK)))
         A2 = R * T(Z + 1, TI - 1) * (1 - ((RHOW * HCW * VZ * DZ) / (2 *
THERMK)))
         A3 = T(Z, TI - 1) * (1 - (2 * R))
         T(Z, TI) = A1 + A2 + A3
         ERR1 = ABS(T(Z, TI) - OLDVAL)
         IF ERR1 > AMAX THEN AMAX = ERR1
       NEXT Z
     NEXT TI

7. Iterations until all values are within 0.01 °C of previous values.
   Then print final results

   IF AMAX < .01 THEN
     PRINT " NUMBER OF ITERATION"; NUMIT
     PRINT #2, USING " NUMBER OF ITTE = ###"; NUMIT
     FOR Z = 1 TO GRIDZ
       FOR TI = 1 TO TT
         PRINT Z, TI, T(Z, TI)
         PRINT #2, USING " ### #### ##.###"; Z; TI; T(Z, TI)
         INPUT "PRESS ENTER TO CONT:"; CH$
       NEXT TI
     NEXT Z
     END
   END IF
NEXT K
.....
END

```